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STRONG POLARIZATION OF THE RESIDUAL NUCLEUS IN A HEAVY-ION INDUCED TRANSFER REACTION

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Résumé. — Dans la réaction $^{16}\text{O}(^{16}\text{O}, ^{12}\text{C})^{20}\text{Ne}^*$, une forte polarisation des niveaux du ^{20}Ne a été observée le long d'un axe perpendiculaire au plan de réaction. Cette polarisation est différente de celle observée lorsque les mêmes niveaux étaient peuplés dans la réaction $(^7\text{Li}, t)$.

Des calculs en DWBA qui reproduisaient les distributions angulaires et la polarisation dans la réaction $(^7\text{Li}, t)$ et qui décrivent encore les distributions angulaires de $(^{16}\text{O}, ^{12}\text{C})$ s'avèrent incapables de reproduire la polarisation correspondante.

Abstract. — A strong polarization of ^{20}Ne levels has been observed in the $^{16}\text{O}(^{16}\text{O}, ^{12}\text{C})^{20}\text{Ne}^*$ reaction along an axis perpendicular to the reaction plane. This polarization differs from that reported in the $(^7\text{Li}, t)$ reaction, when the same nuclear levels were populated. D.W.B.A. calculations which fitted both angular distributions and polarization in the $(^7\text{Li}, t)$ reaction and which can also describe the $(^{16}\text{O}, ^{12}\text{C})$ angular distributions fail to reproduce the associated $^{20}\text{Ne}^*$ polarization.

In a nuclear reaction, the polarization of the residual nucleus usually depends on the reaction mechanism. In a recently reported α -transfer reaction [1], the $^{16}\text{O}(^7\text{Li}, t)^{20}\text{Ne}^*$ reaction, a selective population of the $m = 0$ substate was observed on a quantization axis very close to the recoil direction. It may be noted that this almost aligned state implies that there is no strong polarization along any axis. A calculation using the distorted wave Born approximation (DWBA) was able to reproduce this result [2].

This letter reports polarization measurements of $^{20}\text{Ne}^*$ obtained by ^{12}C - ^{16}O angular correlation in the sequential reaction $^{16}\text{O}(^{16}\text{O}, ^{12}\text{C})^{20}\text{Ne}^* \rightarrow \alpha + ^{16}\text{O}$. The aim of this experiment was to investigate whether the experimental and theoretical results reported above for the case of a light-ion induced transfer would still hold for the case where the same nuclear levels are populated in a heavy-ion induced transfer.

Polarization phenomena in heavy-ion reactions have already been studied for inelastic scattering [3, 4] and transfer reactions [5]. No strong effect was observed for transfer reactions but the measurements were based on the observation of a broadened particle line shape, a technique which yields less information than a correlation measurement.

In the present correlation experiment, the corre-

lation function $W(\theta, \varphi)$, i.e. the probability density for the emission of the decay products in the direction $[\theta, \varphi]$, is given by [6, 7]

$$W(\theta, \varphi) = \left| \sum_m p_j^m (-1)^m e^{-im\varphi} d_{m0}^j(\theta) \right|^2 \quad (1)$$

where the $d_{m0}^j(\theta)$ are the elements of the reduced rotation matrix [8]. Thus, the complex numbers p_j^m which are the components of the polarization tensor of $^{20}\text{Ne}^*$ can be extracted from the experimental correlation.

The experimental study was done at the Orsay MP Tandem. The ^{12}C nuclei emitted from the target were analysed by a magnetic spectrograph and detected with a charge division proportional counter followed by a set of four solid state detectors. The energy resolution was typically 150 keV. In this reaction it is possible to obtain the polarization of $^{20}\text{Ne}^*$ from either the ^{12}C - α or the ^{12}C - ^{16}O angular correlations. The ^{12}C - ^{16}O correlation was chosen since it gives a higher efficiency due to kinematics. A five cm long position sensitive detector located seven cm from the target was sufficient to measure the entire correlation pattern in a given plane. This detector was used in and perpendicular to the reaction plane [9].

Energy spectra and angular distribution of the $^{16}\text{O}(^{16}\text{O}, ^{12}\text{C})^{20}\text{Ne}^*$ primary reaction were studied at 68 MeV and 90 MeV. As can be seen in figure 1, this reaction is selective and only a few states are strongly populated. With the exception of the 5^- at 8.45 MeV,

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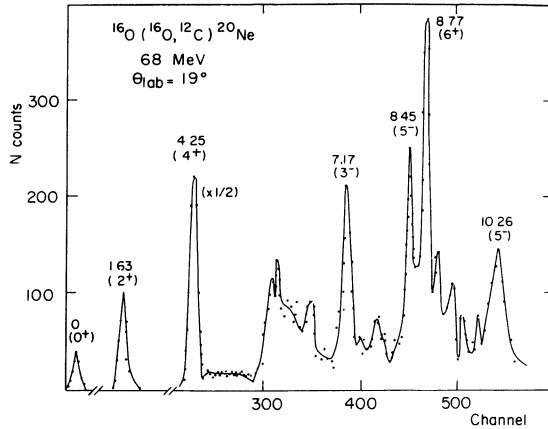


FIG. 1. — ^{12}C energy spectrum measured at 19° for the reaction $^{16}\text{O}(^{16}\text{O}, ^{12}\text{C})^{20}\text{Ne}$ at 68 MeV incident energy.

they are all known to have a large ($^{16}\text{O} + \alpha$) component. The angular distributions (Fig. 2) were measured between 3° and 21° by 1° steps. They are rather flat, somewhat forward peaked and similar for all levels. Calculations carried out with the SATURN-MARS DWBA code [10] reproduce these rather structureless angular distributions well.

The angular correlations have been measured at 68 MeV, both in the reaction plane and in a plane perpendicular to it, for the 7.17 (3^- , $\tau_m = 8.2 \times 10^{-20}$ s), 8.45 (5^-), 8.78 (6^+ , $\tau_m = 6.0 \times 10^{-18}$ s) and 10.26

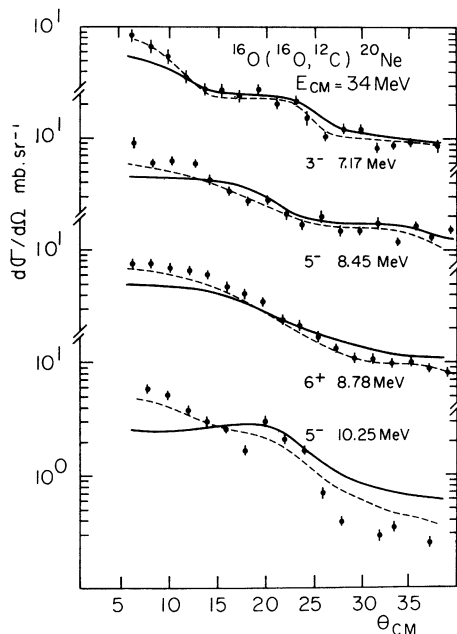


FIG. 2. — Comparison of experimental angular distributions and EFR DWBA calculations. Optical model parameters used are : $V_R = 17$ MeV, $W_I = 7.2$ MeV, $A_R = 0.49$ fm, $A_I = 0.15$ fm, $R_R = 1.35$ fm, $R_I = 1.27$ fm, for the incident channel and $V_R = 17$ MeV, $W_I = 5.8$ MeV, $A_R = 0.49$ fm, $A_I = 0.15$ fm, $R_R = 1.35$ fm, $R_I = 1.27$ fm for the exit channel. The form factors have been calculated as those of slightly bound states ($B = 0.4$ MeV) for the full line curves. Predictions with more strongly bound states ($B = 1.5$ MeV) are also shown (dashed line) to indicate the influence of the form factor. A radius $r_0 = 1.35$ fm and a diffuseness $a = 0.65$ fm have been used for the Woods Saxon wells.

(5^- , $\tau_m = 4.7 \times 10^{-21}$ s) MeV states, for ^{12}C angles of $17^\circ 5$ and $20^\circ 5$. From figures 3 and 4, which show the $17^\circ 5$ data, it can be seen that the correlation is peaked in the reaction plane and that in this plane, simple patterns are observed with rather regular oscillations. Values of the p_j^m have been extracted from the data, using equation (1) with a least square method. Table I gives the populations of the various magnetic substates $|p_j^m|^2$ on a quantization axis perpendicular to the reaction plane for the four excited states of ^{20}Ne studied. One clearly sees the strong polarization of the $^{20}\text{Ne}^*$ for all levels and for the two ^{12}C angles studied since in all cases the population for $m = j$ is by far the largest [11], a result very different from that observed in the ($^7\text{Li}, t$) reaction. Although the $^{20}\text{Ne}^*$ polarization is expected to depend on

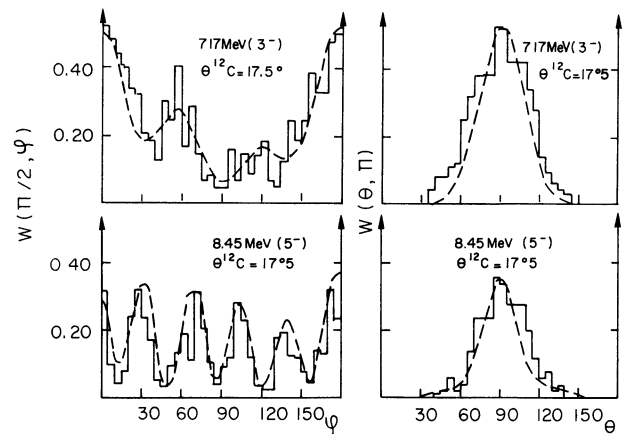


FIG. 3. — ^{12}C - ^{16}O angular correlations measured in the sequential reaction $^{16}\text{O}(^{16}\text{O}, ^{12}\text{C})^{20}\text{Ne}^* \rightarrow \alpha + ^{16}\text{O}$ at 68 MeV incident energy for two of the excited states of the ^{20}Ne . The correlations observed in the reaction plane, ($\theta = 90^\circ$) are shown on the left hand side of the figure while the correlations observed in the perpendicular plane, including the recoil direction ($\phi = 180^\circ$), are shown on the right hand side. The dotted lines correspond to the least square search (based on equation (1)) from which the values of the populations $|p_j^m|^2$, given in table I, are extracted.

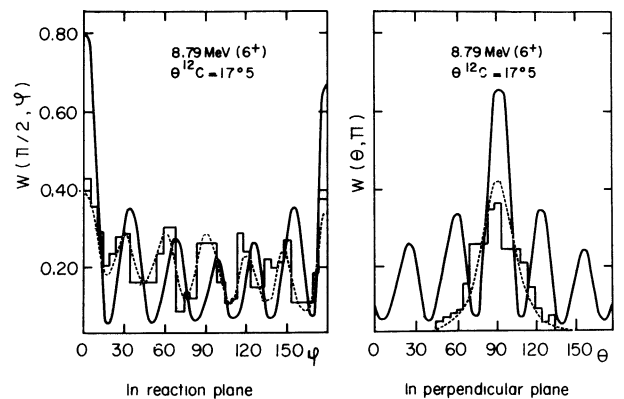


FIG. 4. — Comparison between a DWBA prediction (solid line) and experimental results for the ^{12}C - ^{16}O angular correlations measured in the sequential reaction $^{16}\text{O}(^{16}\text{O}, ^{12}\text{C})^{20}\text{Ne}^* \rightarrow \alpha + ^{16}\text{O}$ at 68 MeV incident energy for the 6^+ (8.79 MeV) state of the ^{20}Ne . The dotted lines correspond to the least square search (based on equation (1)) from which the values of the populations $|p_j^m|^2$, given in table I, are extracted.

TABLE I

Experimental values of the magnetic substate populations $|p_j^m|^2$ on a quantization axis perpendicular to the reaction plane. The sign of the m value for which $|p_j^m|^2$ is dominant is arbitrary (see Ref. [11]). The absolute error is estimated to be $\sim \pm 5\%$.

Excitation energy of the $^{20}\text{Ne}^*$ state (MeV)	Spin and parity	θ (^{12}C)	Populations $ p_j^m ^2$ in %					
7.17	3^-		$m = +3$	$+1$	-1	-3		
		$17^\circ 5$	4	1	16	79		
		$20^\circ 5$	5	2	5	88		
8.45	5^-		$m = +5$	$+3$	$+1$	-1	-3	-5
		$17^\circ 5$	17	1	3	11	11	56
		$20^\circ 5$	6	2	0	0	2	90
8.79	6^+		$m = +6$	$+4$	$+2$	0	-2	-4
		$17^\circ 5$	5	0	2	1	1	3
		$20^\circ 5$	1	0	1	1	1	3
10.25	5^-		$m = +5$	$+3$	$+1$	-1	-3	-5
		$17^\circ 5$	1	1	3	14	14	66
		$20^\circ 5$	5	1	0	8	3	83

the ^{12}C angles [2], the strong polarization observed for all levels and for two ^{12}C should be, however, dependent on the mechanism.

The angular correlation functions have been compared to the DWBA population using parameters which gave good fits for the angular distributions (Fig. 2). Figure 3 shows the strong disagreement, particularly in the vertical plane, between these calculations and the present experimental data. This disagreement appears to be insensitive to the parameters used and the calculations always give a selective population of the $m = 0$ substate on a quantization axis close to the recoil direction. As observed above such a population was found experimentally in the (^7Li , t) reaction and then well reproduced by DWBA. Calculations taking into account the unbound nature of the states studied should not change these results ⁽¹⁾. Interestingly, an intuitive classical argument can account for the observed predominance of polarization along the axis perpendicular to the reaction plane. If the incident and outgoing nuclei, as well as the transferred fragment, are assumed to move in the

reaction plane, the transferred angular momentum and hence the $^{20}\text{Ne}^*$ spin, is expected to be perpendicular to this plane as observed in our data. This might indicate that, although the mechanism is different from the one assumed in DWBA, the symmetry properties implied in the intuitive description remain valid.

In conclusion, a strong polarization of the residual nucleus along an axis perpendicular to the reaction plane has been experimentally observed in the $^{16}\text{O}(^{16}\text{O}, ^{12}\text{C})^{20}\text{Ne}^*$ reaction for two ^{12}C angles close to the grazing angle. DWBA calculations, which were found to account for the angular distributions, fail to reproduce this polarization. Angular correlation measurements, which give the reaction amplitudes and the population of the magnetic substates, provide detailed information on the reaction mechanism. This is particularly useful when the angular distributions are structureless as is often the case for heavy-ion transfer reactions.

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See also HARRIS, J. W. *et al.*, *P.R.L.* **38** (1977) 1460 where a correlation study concerning the (^{16}O , ^{12}C) reaction on ^{27}Al is reported, but for a 10 MeV wide peak at ~ 15 MeV excitation energy in the $^{31}\text{P}^*$ spectrum.

[6] This formula is restricted to the case where all the fragments

involved in the sequential reaction have a spin zero, with the exception of the intermediate nucleus only.

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[8] They are related to the associated Legendre polynomials by :

$$d_{m0}^j(\theta) = (-1)^m [(j - |m|)! / (j + |m|)!]^{1/2} p_j^{|m|}(\cos \theta).$$

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[11] It is seen from formula (1) that the substitution of every p_j^m by $(p_j^{-m})^*$ leaves $W(\theta, \varphi)$ unchanged and consequently the direction, up or down, of the polarization cannot be determined by the present measurements. It is likely however that if the transfer occurs essentially on one type of trajectory it is the one with positive deflection angles.